



AIRBUS

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Future Position Prediction for Pressure Refuelling Port of
Commercial Aircraft

School of Aerospace, Transport and Manufacturing
Computational and Software Techniques in Engineering

MSc
Academic Year: 2023–2024

Supervisors: Dr Boyu Kuang and Dr Stuart Barnes
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for the degree of MSc.

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- the thesis submitted has been written by me alone.
- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
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Acknowledgements

The author would like to thank ...

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List of Abbreviations

ML	Machine Learning
DL	Deep Learning
AI	Artificial Intelligence
CNN	Convolutional Neural Network
RNN	Recurrent Neural Network
LSTM	Long Short-Term Memory
GRU	Gated Recurrent Unit
EKF	Extended Kalman Filter
AAGR	Autonomous Aircraft Ground Refueling
AGR	Aircraft Ground Refueling
UAV	Unmanned Aerial Vehicle
AAR	Autonomous Aerial Refueling
DGPS	Differential Global Positioning System
SVM	Support Vector Machine
HOG	Histogram of Oriented Gradients
SOTA	State-of-the-Art
AIS	Automatic Identification System
GPS	Global Positioning System

Chapter 1

Introduction

Ground pressure refuelling is a standard method used to refuel commercial aircraft safely and efficiently. This process involves using a hydrant system, which consists of underground fuel pipelines connected to a network of fuel hydrants located at aircraft parking positions [4]. The hydrant system is supplied with fuel from storage tanks, typically located near the airport [25].

When an aircraft is ready for refueling, a hydrant dispenser vehicle, also known as a hydrant truck or cart, is connected to the hydrant pit using a flexible hose [39]. The hydrant dispenser vehicle is equipped with a pressure control valve, a flow meter, and a filtration system to ensure that the fuel meets the required quality standards [2].

The refueling process begins by connecting the hydrant dispenser vehicle to the aircraft's fuel panel using another flexible hose [39]. The pressure control valve on the hydrant dispenser vehicle is then used to regulate the fuel pressure and flow rate, ensuring that the fuel is delivered to the aircraft at the appropriate pressure and volume [2].

One of the main advantages of pressure ground refueling is its efficiency. This method allows for high fuel flow rates, which can significantly reduce aircraft turnaround times [4]. Additionally, the use of underground pipelines eliminates the need for fuel trucks, reducing traffic congestion and the risk of accidents on the apron [25].

Safety is another critical aspect of pressure ground refueling. The hydrant system is designed with multiple safety features, such as emergency shutdown valves and leak detection systems, to minimise the risk of fuel spills and fires [2]. Moreover, the hydrant dispenser vehicles are equipped with safety devices, such as dead man switches and bonding cables, to prevent incidents during the refueling process [39].



Figure 1.1: Pressure Refuelling of a Commercial Aircraft. Source: Tom Boon/Simple Flying

The aviation industry is undergoing a significant transformation with the advent of intelligent airports based on highly automated systems. Among these, automated refuelling systems play a crucial role in ensuring efficient and accurate refuelling of aircraft. However, one of the main challenges of this automation process is the accurate detection of the aircraft's refuelling port, which is relatively small and can easily be obscured by other visual elements on or near an aircraft. Scanning the entire area of each video frame is both time-consuming and inaccurate. It is therefore essential to develop a more efficient and accurate method of locating the refuelling port.

This thesis aims to address this challenge by developing a new AI model that uses the temporal relationships between successive frames of a video to predict the location of the refuelling port in subsequent frames. By focusing the analysis on the most relevant areas of the video sequence, this approach has the potential to optimise both the speed and accuracy of the refuelling system.

Specific objectives of this thesis include conducting a comprehensive review of state-of-the-art object detection and tracking methods, designing and developing a real-time computer vision system capable of accurately detecting and tracking the pressurised refuelling port of a commercial aircraft, the implementation and evaluation of deep learning time series models for future position prediction, the integration of Extended Kalman Filtering (EKF) into deep learning models to improve the accuracy and robustness of future position predictions, and the development of a real-time framework for predicting the future position of the pressurised refuelling port.

By achieving these objectives, this thesis aims to make a significant contribution to the development of intelligent airport systems and to improve the efficiency and accuracy of automated refuelling systems at airports, while reducing computing power requirements. The proposed framework has the potential to be applied in various scenarios, such as different lighting conditions, angles and orientations of refuelling ports, making it a versatile and effective solution to the challenges of automated refuelling systems.

Chapter 2

Literature Review

2.1 Automated Refuelling Systems in the Aviation Industry

Automated refueling systems have gained substantial importance in the aviation industry due to their potential to enhance safety and efficiency. The concept of Autonomous Aircraft Ground Refueling (AAGR) emerged in the 1980s, with initial implementations featuring numbered markers near refueling ports to aid in image processing and robotic automation [41, 3, 26].

These systems streamline the refuelling process by using state-of-the-art mechanisms and technologies to ensure accuracy and speed. A key element is the pressurised fuel adaptor, which connects seamlessly to the aircraft [54]. Methods such as ‘PosEst’ have been proposed to capture and track objects in 3D, enabling the pressurised refuelling port to be located precisely. [55].

In addition, autonomous in-flight refuelling technologies for Unmanned Aerial Vehicles (UAV-AARs) have also been developed to extend their range, endurance and payload capacity without significantly altering their original design. This technology overcomes limitations in fuel capacity and endurance, enabling UAVs to undertake longer missions [17].

The implementation of AAGR presents a number of challenges, including varying lighting conditions, different refuelling port designs and potential obstructions. Confidentiality issues associated with aircraft refuelling data, as well as the lack of standardised workflows, also complicate the deployment of advanced AAGR solutions, based on [26] data.

Accurately detecting and estimating the position of the fuelling adaptor is a major hurdle. Current methods that rely on artificial features often encounter occlusions and suffer from reduced reliability due to a low signal-to-noise ratio, particularly over long distances [55]. Variability in lighting, weather conditions and the physical state of the refuelling adapter further complicates detection and localisation [56]. Vision-based systems must operate in real time and with minimal computational load, adding a new layer of complexity.

The development of high-quality data sets for training and monitoring automated refuelling systems is another major challenge. Collecting and processing these datasets is often time-consuming and requires meticulous configuration [54].

Visual measurement methods based on artificial features, such as spray marks or LEDs, are commonly used in today’s automated refuelling systems. The VisNav system, developed by Valsek, uses light-emitting diodes emitting at different frequencies to locate the centre of a beacon, employing a Gaussian least squares differential correction algorithm to calculate the position of the [55] refuelling adaptor. Despite the advantages of these methods, they remain sensitive to occlusion and low signal-to-noise ratios at long distances.

Recent advances in Automatic Aircraft Ground Refuelling (AAGR) rely on computer vision, artificial intelligence and robotics to achieve high levels of automation. The integration of these technologies with Big Data has significantly improved the feasibility and accuracy of AAGR systems thanks to the creation of large datasets for training and validation. For example, an Aircraft Ground Refuelling (AGR) dataset comprising more than 3,000 images from 13 databases was expanded to more than 26,000 images after augmentation, enabling AGR scene recognition through image mining, augmentation and classification [26]. In addition, recent innovations have introduced hybrid datasets combining real and synthetic data for training and validating [56] systems. This approach offers a wide range of scenarios and conditions, improving the robustness and accuracy of automated refuelling systems.

Furthermore, in the field of autonomous aerial refuelling, current technologies rely mainly on vision-based systems and sophisticated control algorithms. These methods use a variety of sensors, including monocular and binocular cameras, to detect and track drugs and refuelling probes. Wang et al. [48] demonstrated the feasibility of real-time drug recognition and 3D localisation for autonomous aerial drone refuelling using monocular computer vision. In addition, Chen and Stettner [6] explored the application of 3D flash lidar for drug tracking [48]. The probe and drogue refuelling system involves the refuelling aircraft towing a refuelling hose with a drogue at the end, while the pilot of the receiving aircraft manoeuvres to insert the probe into the drogue. For unmanned aerial refuelling, this process is carried out autonomously. Although DGPS offers high location accuracy, it faces challenges such as lock-in problems and low bandwidth in air-to-air refuelling applications [59].

2.2 Object Detection and Tracking in Computer Vision

In Computer Vision, Object Detection refers to the identification and location of individual objects within an image, providing both spatial information (bounding boxes) and confidence scores, which represent the probability that each detected object belongs to the predicted class [11]. For example, in the following image, there are five detections, including one ‘ball’ with a confidence level of 98% and four ‘people’ with confidence levels of 98%, 95%, 97% and 97%.

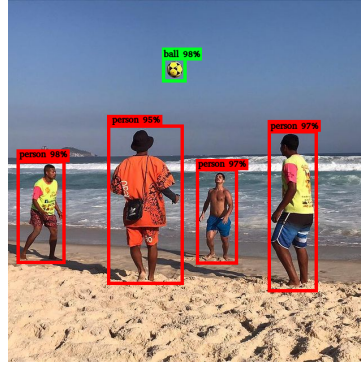


Figure 2.1: Example of outputs from an object detector [11].

Over the last few decades, Object Detection models based on Deep Learning have enjoyed remarkable success. These models fall into two main categories: two-stage detectors and single-stage detectors.

On the one hand, two-stage detectors, such as R-CNN [16], Fast R-CNN [15], Faster R-CNN [37] and R-FCN [10], first generate region proposals and then refine these proposals into precise anchor boxes. While these models excel in detection accuracy, they typically suffer from large model sizes and slower detection speeds [23, 53].

On the other hand, single-stage detectors, including the SSD (Single Shot Multibox Detector) [33], YOLO (You Only Look Once) series [36, 35, 5, 8, 14, 21, 30, 22, 47, 50, 46, 52, 45], and RetinaNet [31] directly predict object locations and categories in a single network pass. These models are known for their high detection speeds but sometimes compromise accuracy [23, 53].

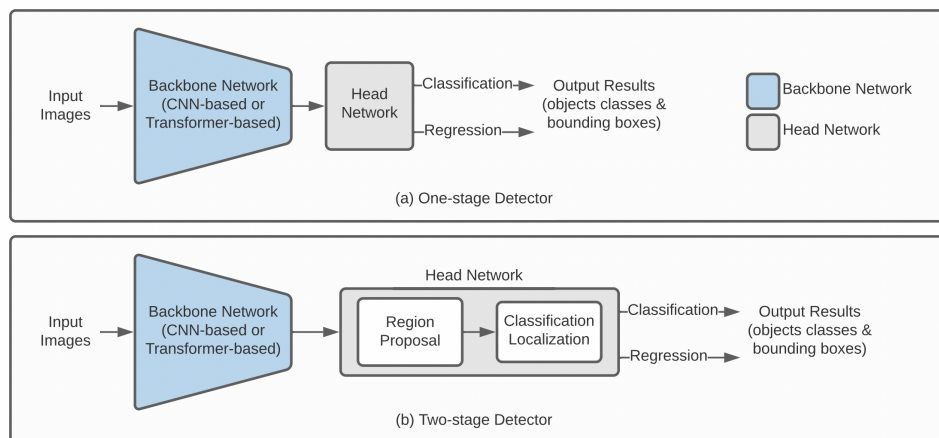


Figure 2.2: Basic deep learning-based one-stage vs two-stage object detection model architectures [23].

Evaluating Object Detection models involves several key metrics to measure their performance. One common metric is Intersection over Union (IoU), which measures the overlap between a predicted bounding box and a ground-truth bounding box, as shown in Figure 2.3.

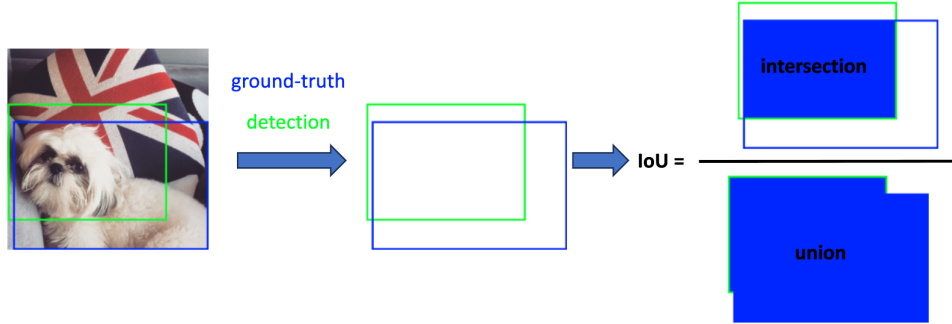


Figure 2.3: Intersection over Union (IoU) between a detection (in green) and ground-truth (in blue). [11]

Based on the IoU metric, a detection can be classified as a **True Positive (TP)** or a **False Positive (FP)** depending on whether the IoU value exceeds a certain threshold (T_{IoU}). If the IoU is above the threshold, the detection is considered correct (TP); otherwise, it is classified as a False Positive (FP). Additionally, **False Negatives (FN)** refer to ground truth objects not detected by the model, while **True Negatives (TN)** are correctly classified background detections [11]. These classifications allow for the calculation of the following metrics:

- **Precision:** The ratio of True Positives to the total number of detections, measuring the model's ability to avoid false positives:

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}} \quad (2.1)$$

- **Recall:** The ratio of True Positives to the total number of ground-truth objects, measuring the model's ability to avoid false negatives:

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}} \quad (2.2)$$

Common metrics used to evaluate Object Detection include:

- **Average Precision (AP):** This combines precision and recall, providing a single figure summarizing the model's performance across different confidence thresholds. Common versions are AP@.5 (with a threshold of 0.5 IoU) and AP@[.5:.05:.95] , which calculates the average of AP values over several IoU thresholds [11].
- **Average Recall (AR):** This measures the recall of the model averaged across multiple IoU thresholds. It can be computed for different numbers of detections per image, such as AR@1 , AR@10 , etc. [11].
- **Inference Time:** The time taken by the model to process an image, which is critical for applications requiring real-time detection [11].
- **Model Size:** The number of parameters or the size of the model, affecting deployment, especially on devices with limited resources [11].

- **Efficiency:** This considers the trade-off between accuracy and speed, often visualized using the AP vs. inference time curve [11].

In addition to Object Detection, Object Tracking is another critical task in Computer Vision, involving the continuous monitoring of objects across video frames. Object Tracking methods can be broadly classified into two categories: **Generative Trackers** and **Discriminative Trackers** [7]. Generative trackers are capable of handling challenging scenarios such as occlusion and large-scale variation through particle sampling strategies, often integrated with various appearance models, including sparse representation and energy of motion. Discriminative trackers, by contrast, build robust classifiers using hand-crafted or deep features [7]. The combination of generative and discriminative approaches, as well as the integration of deep learning techniques such as fully revolutionary networks and Transformer models, has led to significant improvements in object detection performance [32, 58, 57]. In addition, the speed and computational requirements of these algorithms are critical factors influencing their practical applicability [58, 57, 27]. Advanced techniques in object tracking leverage both generative and discriminative models to amplify tracking efficacy. The utilisation of deep trackers has evidenced superior results on public tracking datasets, attributed to their potent feature extractors, accurate bounding box regressors, and discriminative classifiers [27]. Techniques such as deformable convolution and Transformer models extend traditional convolution or correlation methodologies to execute global feature matching, thereby enhancing tracking accuracy. The incorporation of contextual or knowledge information can substantially elevate performance, with methodologies like Particle Filtering, also recognised as Sequential Monte Carlo (SMC) methods, framed as problems of Bayesian inference in state space [9, 49]. The extended Kalman Filtering (EKF) is another advanced technique that has been employed to improve tracking accuracy by predicting the current status through the previous status and modifying the prediction result based on observation information [58, 57]. Despite these advancements, the integration of these methods in a complementary manner remains an open research area with substantial potential for advancing the field [32, 58].

2.3 Deep Learning for Spacio-Temporal Prediction

Time series prediction involves processing sequential data to predict future events or values. Various deep learning models have been applied to this task, requiring several preparatory steps such as collecting data, designating attribute types, dealing with inconsistencies and storing datasets. These datasets are usually classified into units of time such as seconds, minutes and hours, allowing the construction of metadata for machine learning [29].

Early Approaches and Models

The problem of predicting the future locations of objects has been extensively studied, particularly for static surveillance cameras. Initial efforts utilised recurrent neural networks (RNNs), including long-term memory networks (LSTMs) and gated recurrent units (GRUs), in an encoder-decoder format to encode past observations and decode future locations. Early models integrated additional inputs such as environmental data and semantic actions to enhance prediction accuracy. For instance, Alahi et al. [1] proposed a Social-LSTM to model pedestrian trajectories and interactions, further improving global context capture through a social pooling module [24]. Recent advancements have leveraged generative models and attention mechanisms to manage complex scenes involving multiple interacting agents [24].

Frame-Based Approaches in Spatio-Temporal Prediction

Video prediction, a critical task in spatio-temporal data analysis, involves forecasting future frames based on past and current frames. This process requires understanding both spatial and temporal dynamics within the data.

Convolutional LSTM (ConvLSTM)

ConvLSTM integrates convolutional operations into LSTM units to better capture spatial features in addition to temporal dependencies [42]. By processing video data as sequences of frames, ConvLSTM effectively models the spatio-temporal dependencies necessary for accurate video prediction. Each frame serves as a spatial unit, and the sequence of frames provides temporal context, allowing the model to predict future frames by learning from the patterns in previous ones.

Cubic LSTM for Video Prediction

The Cubic Long Short-Term Memory (CubicLSTM) unit, as proposed by Fan et al. [12], extends the capabilities of ConvLSTM by separately processing spatial and temporal information through three branches: temporal, spatial, and output. This approach mitigates the computational burden and enhances prediction accuracy. Specifically:

- The *temporal branch* processes motion information by analysing the sequence of frames over time.
- The *spatial branch* captures object information within individual frames.
- The *output branch* combines temporal and spatial information to generate predicted future frames.

This separation of concerns allows the model to handle the complexities of video data more effectively, resulting in more accurate predictions of future frames.

Dual-Branch Spatial-Temporal Learning Network

Huang and Guan [19] proposed a dual-branch video prediction network that aims to generate high-quality future frames by simultaneously capturing complex motion patterns and preserving appearance information. Their network includes two distinct units:

- The *motion prediction unit (MPU)* focuses on inter-frame motion and intra-frame appearance by using depth and multiple-scale convolutions, along with temporal attention mechanisms to enhance feature interactions over time.
- The *spatial prediction unit (SPU)* concentrates on spatial information, ensuring appearance consistency across video frames by capturing various appearance features.

This dual-branch approach addresses the limitations of relying on external information or complex state transition units, resulting in better visual quality and fewer blurry artifacts in predicted frames.

Unsupervised Video Forecasting with Flow Parsing

Jin et al. [20] introduced an unsupervised video forecasting approach that incorporates a flow parsing mechanism. This model separates the motion and appearance learning processes:

- The *motion stream* predicts optical flow between frames to capture dynamic changes.
- The *appearance stream* reconstructs frames to preserve spatial details.

By integrating these streams, the model can predict future frames with improved motion accuracy and appearance fidelity.

Joint Optimization with Synthesis and Optical Flow Estimation

Ranjan et al. [34] proposed a method that jointly optimizes frame synthesis and optical flow estimation. Their approach leverages:

- A *frame synthesis network* to generate predicted frames.
- An *optical flow estimation network* to capture motion dynamics between frames.

This joint optimization enhances the model's ability to produce accurate and visually coherent future frames.

Predicting Future Frames for Fast-Moving Objects with Motion Blur

Lee et al. [28] addressed the challenge of predicting future frames for fast-moving objects, which often result in motion blur. Their model includes:

- A *motion deblurring module* to reduce blur effects in fast-moving scenes.
- A *future frame prediction module* that leverages the deblurred frames to enhance prediction accuracy.

This approach ensures that the predicted frames maintain high visual quality even in challenging conditions.

Applications and Case Studies

In various applications, the frame-based approach to spatio-temporal prediction has proven highly effective:

Moving-MNIST Dataset

The Moving-MNIST dataset consists of sequences of moving handwritten digits. Each sequence includes a series of frames, and the goal is to predict future frames based on the observed ones. The CubicLSTM-based CubicRNN demonstrated superior accuracy compared to traditional ConvLSTM models, showcasing its ability to capture both motion and spatial features effectively [43, 12].



Figure 2.4: 2-digit Moving MNIST data [43]

Robotic Pushing Dataset

This dataset involves sequences of robotic arms pushing objects, with each frame representing a step in the sequence. The CubicLSTM model, combined with convolutional dynamic neural advection (CDNA) models, achieved higher accuracy and generated clearer frames compared to ConvLSTM and CNN-based models. This application highlights the importance of accurately predicting future frames to understand and anticipate the movements of robotic systems [13, 12].

KTH Action Dataset

The KTH Action dataset features videos of people performing various actions, with each video divided into frames. The CubicLSTM model provided more accurate and visually consistent predictions of future frames compared to other state-of-the-art models like DrNet and MCnet. This demonstrates the model's effectiveness in understanding and predicting human actions over time [40, 12].

UCF Sports Dataset

Huang and Guan's dual-branch network was tested on the UCF Sports dataset, which includes complex motion patterns and large movements. Their method outperformed other state-of-the-art methods in terms of visual quality and motion accuracy, as evidenced by superior metrics such as PSNR, SSIM, and LPIPS. The results validate the network's ability to handle intricate video prediction tasks without relying on additional information [38, 19].

Transformer Models for Frame-Based Prediction

Transformer model, introduced by Vaswani et al. [44], has revolutionised sequence modeling with its efficient and powerful network structure. For video prediction, transformers leverage self-attention mechanisms to capture long-range dependencies across frames. The Hong et al. [18] study shows how transformers can effectively learn mobility patterns from historical frame sequences, achieving state-of-the-art performance in next-location prediction tasks.

Validation and Efficacy

Extensive experiments and validations on real-world datasets have affirmed the efficacy of frame-based models like ConvLSTM, CubicLSTM, and the dual-branch network in improving prediction accuracy. The work of Xu et al. [51] discusses the application of transformers and self-attention mechanisms in sequence prediction, highlighting their effectiveness in various contexts. These models demonstrate the importance of frames as fundamental units of analysis in spatio-temporal prediction tasks.

By leveraging deep learning techniques, especially advanced models like CubicLSTM, dual-branch networks, and transformers, the accuracy and efficiency of spatio-temporal predictions can be significantly enhanced, contributing to improved outcomes in various real-world applications.

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Appendix A

Ethical Approval Letter

Insert your Ethical Approval Letter as the first appendix.

Appendix B

Extra Data

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